Time Estimation for Sinking EDM Operations

W. Vanderauwera, B. Lauwers
Department of Mechanical Engineering, Division PMA, K.U.Leuven, Leuven, Belgium
Email：wouter.vanderauwera@mech.kuleuven.be, bert.lauwers@mech.kuleuven.be

Abstract
Although EDM is widely used in industry, little research has been undertaken into the complex problem of accurately estimating the machining time. Often estimation errors of 200% and more occur. This paper introduces a new concept for accurately estimating the machining time for sinking EDM operations. The concept is based on machine dependent reference values on which a correction factor is applied to take deviations from the reference, due to flushing and efficiency, into account. A validation of the proposed concept showed that for the machining of prismatic cavity shapes a huge reduction of the estimation error is achieved compared to existing methods.

Keywords:
Time estimation, Sinking EDM

1 INTRODUCTION

Electrical discharge machining (EDM) is one of the most widely used non-traditional machining processes in the mould making and precision sector. One of the variants of EDM is sinking EDM in which a preshaped electrode moves into the workpiece. The result of such an operation is a cavity which has the negative shape of the electrode. Unlike traditional processes the machining speed of EDM operations depends on the process conditions. This means that one needs to have an idea of the process conditions in order to make an estimation of the EDM time. Research has been carried out in which especially the influence of electrical parameters (e.g. discharge current i_e, discharge duration t_e) on the machining speed has been investigated [1,2]. Besides the electrical parameters also the flushing conditions affect the machining speed [3]. Rather less attention has been paid to the quantification of the effect of flushing related parameters on machining speed and EDM time. Even by knowing the effect of all these parameters accurate EDM time estimations were not always possible in the past due to the often unpredictable behaviour of the process. Time estimations were mostly based on rules of thumb or based on values for the material removal rate (MRR) determined by the machine tool builders. These values are determined with simple electrodes under ideal flushing conditions. As a result estimation errors of 200% and more occurred even when estimated by experienced persons [4]. The recent development of automated flushing techniques and optimisation of machine controllers increased the reliability of the process and cleared the way for accurate EDM time estimations. However, little research has been conducted in developing a systematic approach for accurately estimating the EDM time. The most pronounced result that can be found in literature is the development of an EDM time estimation software tool, named EDcam [4], but with limited results. This paper proposes a new concept for estimating the machining time of sinking EDM operations by taking the effect of flushing and efficiency related parameters into account. This study mainly focused on time estimations for machining cases having a prismatic geometry because these appear in most of the cases in practice. It is investigated whether more accurate results can be obtained compared to existing EDM time estimation methods.

2 CONCEPT OF EDM TIME ESTIMATION

In this study EDM time estimations are based on reference values for the EDM time. For every generator setting of an EDM technology a reference value needs to be determined. In this way the influence of electrical parameters like i_e and t_e is already included. These reference values are determined by a so called calibration procedure which consists of machining cylindrical cavities with predefined dimensions and logging the corresponding EDM times. The way in which the calibration is performed resembles more to the daily practice use of EDM compared to the way in which EDM machine tool builders determine their characteristic values. By performing this calibration procedure for every EDM machine also the machine characteristics (e.g. behaviour of electrode pulsation, protection measures) are largely included.

A time estimation solely based on reference values will not give accurate results. Initial experiments showed that deviations from the reference values occur when comparing different machining cases although machined with identical generator settings on the same EDM machine. These deviations are the result of a difference in debris density in the sparking gap. The debris density is mainly influenced by two groups of parameters: flushing related parameters (e.g. active area, machining depth) and efficiency related parameters (e.g. i_e, t_e, t_o, current density). In the concept of this study deviations are taken into account by correcting the reference values. This correction is dependent on the machining case and is therefore function of factors causing the deviation. Not only between machining cases deviations from the reference values occur (e.g. deviations due to a different cavity shape) but also within a machining case the deviation can fluctuate (e.g. variation of MRR caused by the machining depth). A consequence of this is that the correction on the reference values needs to be dependent on the variation of influencing parameters during an EDM operation. Because of this the EDM time is estimated as a summation of EDM times of small machining steps. Equation 1 shows this summation for the case of an EDM operation with only one generator setting.

$$\text{EDM Time} = \sum_{i=1}^{n} C_i \cdot \text{time}_{ref} \tag{1}$$

With: i the *i*th calculation step;

n the total number of calculation steps;

C_i the correction on the reference time;

time_{ref} the reference EDM time.

In standard EDM operations two kinds of operations can be distinguished namely roughing and finishing operations. Roughing operations refer to the part of an EDM operation in which high energetic generator settings are used in combination with a sinking electrode movement. These operations remove the bulk of the material in a relatively fast way. On the other hand finishing operations refer to the part of an EDM operation in which low energetic generator settings are used in combination with either a sinking or a planetary electrode movement. The purpose of these operations is to obtain the desired end roughness. Initial experiments showed that for both operation types different parameters influence the EDM time. Consequently different analytical models have been developed both based on the general concept given in Equation 1 (see section 3 and 4). Following the distinction between roughing and finishing operations the total EDM time is estimated as the summation of the estimated roughing and finishing time.

The next sections discuss the elaboration of the concept for roughing and finishing operations. All experiments in this study have been performed on an EDM die sinking machine, type AgieCharmilles FO350γ, with Total MS 7000 as dielectric. Copper was used as electrode material and hardened steel (Sverker 21) as workpiece material. During these experiments only the standard electrode pulsation was used for flushing.

3 TIME ESTIMATION FOR ROUGHING OPERATIONS

3.1 Formulation of EDM roughing time

During EDM roughing operations the bulk of the cavity material is removed. In fact, these operations can be seen as volume removal operations in which the volume exerts a large influence on the EDM time. To decouple the influence of the volume from the influence of other parameters affecting the EDM time, the MRR [mm³/min] has been chosen as the reference parameter (MRR_{ref}). MRR_{ref} is determined by the calibration procedure. This procedure consists of machining cylindrical cavities with a depth of 20mm in steps of 1mm for every generator setting with a fixed current density of 9A/cm². For each millimeter MRR_{ref} is calculated. As a result MRR_{ref} is function of the machining depth.

For roughing operations the correction on the reference values will be split up into two correction factors: a flushing factor ($C_{flushing}$) and an efficiency factor ($C_{efficiency}$). These factors are function of parameters influencing the debris density in the sparking gap and resulting in a deviation from the reference. $C_{flushing}$ corrects MRR_{ref} for the effect of flushing related parameters (e.g. frontal electrode area, machining depth) on the EDM roughing time. On the other hand $C_{efficiency}$ corrects MRR_{ref} for the effect of efficiency related parameters (e.g. current density). Applied to the common case of an electrode with multiple identical protrusions (see Figure 1) $C_{flushing}$ takes the effect of the flushing conditions of one protrusion into account. Due to a difference in current density $C_{efficiency}$ takes the additional effect of having more than one of these protrusions into account.

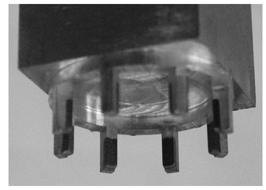

Figure 1: Electrode with multiple identical protrusions.

Following Equation 1 the EDM roughing time is calculated as a summation of EDM times, each representing the machining of an incremental volume along the sinking direction (Figure 2). Equation 2 shows the formulation of the EDM roughing time for the case of using only one generator setting during the roughing operation.

$$\text{EDM Time}_{roughing} = \sum_{i=1}^{n} \frac{\text{Volume}_i}{C_{efficiency_i} \cdot C_{flushing_i} \cdot MRR_{ref_i}} \tag{2}$$

With: i the *i*th calculation step;

n the total number of calculations steps;

Volume_i the volume removed during the *i*th step;

MRR_{ref} the reference MRR for the *i*th step.

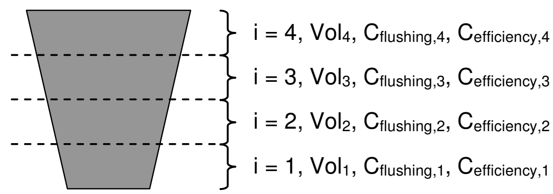

Figure 2: Incremental calculation of EDM roughing time.

3.2 Modelling of correction on MRR_{ref}

A large number of parameters influence the EDM roughing time. In this study only the most important parameters were considered in order to make an accurate EDM time estimation possible for rather simple machining cases. These parameters were either related to $C_{flushing}$ or $C_{efficiency}$ by investigating their effect on the MRR. The relation between MRR and the correction factors is given in Equation 3.

$$MRR(\text{depth}) = C_{efficiency} \cdot C_{flushing} \cdot MRR_{ref}(\text{depth}) \tag{3}$$

Modelling of $C_{efficiency}$

The initial purpose of $C_{efficiency}$ was to include the effect of multiple identical protrusions into the time estimation (see Figure 1). The current density [A/cm²], defined as the mean current divided by the active frontal electrode area, is a good parameter to characterize this effect. The mean current is calculated based on parameters like maximal current, t_e, t_0 and the servo parameter. To examine the effect of the current density on the MRR machining experiments were performed in which the current density was varied by varying both the frontal surface area and the mean current (see Table 1). Each experiment consisted of a machining operation until a depth of 1mm was reached and determining the resulting MRR. Each experiment was performed 3 times. The determined MRR was compared to $MRR_{ref}(0\text{-}1)$ resulting from the calibration procedure for machining between 0 and 1mm in depth. According to Equation 3 the total correction was calculated. In order to determine $C_{efficiency}$, $C_{flushing}$ needs to be known. $C_{flushing}$ for these experiments was determined by performing an extra experiment for each frontal area at a fixed current density of 9A/cm². Because MRR_{ref} is also determined at 9A/cm² $C_{efficiency}$ equals 1 for these experiments. Consequently the total correction is equal to $C_{flushing}$.

Frontal Area [mm²]	Mean current [A]	$C_{flushing}$	$C_{efficiency}$
39	9/13.4/19.9	1.26	0.96/0.62/0.35
75	9/13.4/19.9	1.46	1.1/0.75/0.63
100	6.7/13.4	1.68	1.07/0.75
150	6.7/9	1.21	1.2/1.4
360	3.5/6.7/9/13.4	1.14	1.35/1.3/1.4/1.4

Table 1: Testing plan and results for $C_{efficiency}$.

By using a test setup similar to the one shown in Figure 3 the flushing conditions could be held constant during each experiment. In this setup a cylindrical workpiece is machined with a cylindrical electrode of the same diameter so that the top of the workpiece is removed layer-by-layer. The results of these experiments are listed in Table 1 and shown graphically in Figure 4. This figure clearly shows that $C_{efficiency}$ decreases when higher current densities are used. Note that $C_{flushing}$ given in Table 1 is only valid for the test setup in Figure 4.

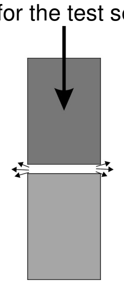

Figure 3: Test setup for $C_{efficiency}$.

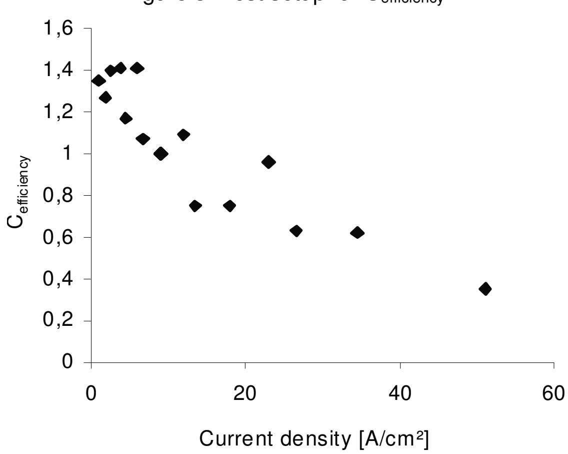

Figure 4: Relation between $C_{efficiency}$ and current density.

Modelling of $C_{flushing}$

The flushing factor refers to the part of the deviation from the reference value caused by the flushing conditions. This factor was determined by correlating flushing related parameters to it. In this study only the machining depth and the frontal surface area were considered as influencing parameters. Machining experiments were performed in which rectangular cavities were machined with machining depths ranging from 1mm to 20mm with steps of 1mm and with varying frontal surface area (see Table 2). Each experiment was performed 3 times and as a result the MRR was determined. With the knowledge of MRR_{ref} and $C_{efficiency}$ (estimated by the trend from Figure 4) $C_{flushing}$ was calculated according to Equation 2. From these experiments some conclusions can be drawn. Firstly these experiments showed that the machining depth strongly affects the MRR. This can be clearly seen in Figure 5 which shows the results of some experiments together with the MRR_{ref} for the applied generator setting. This figure shows that especially for small machining depths the effect on the MRR is clear. This figure also indicates that the influence of the machining depth is affected by the current density. This can be explained by considering the debris density in the sparking gap. In [5] it is stated that an optimal debris density exists which results in an optimal MRR. Experiments showed that besides the flushing conditions also the current density affects the debris density (an increase of the current density results in an increase of the debris density). Applied to Figure 5, the combined effect of a low current density and an increasing machining depth results in a more optimal debris density (especially for small depths). As a result an increase of the MRR can be noted. In case of high current densities initially more debris are generated but due to the varying flushing conditions resulting from an increase of the machining depth the debris density becomes larger than the optimal value. This results in a decrease of MRR.

Mean Current [A]	Frontal Area [cm²]	Number of Protrusions	Current Density [A/cm²]
2.4	0.25/0.5	1/1	9.6/4.8
3.46	0.25/0.5	1/1	13.8/6.9
6.72	0.25/0.5/0.75/1	1/1/1/1	26.9/13.4/9/6.7
9	0.5/1	1/1	18/9
13.44	0.5/1/1/1.5/1.5/ 2/3	6/1/2/1/2/ 1/1	4.5/13.4/6.7/9/4.5/ 6.7/4.5
20	1/1/2/2/3	1/2/1/2/1	20/10/10/10/5/6.7
32	0.5/1/1/1.5/2/ 3/3/4/6	6/1/2/2/1/ 1/1/1/1	11/32/16/11/16/ 11/11/8/5.3
45.51	1/4	2/1	22.76/11.38

Table 2: Experiments for determining $C_{flushing}$.

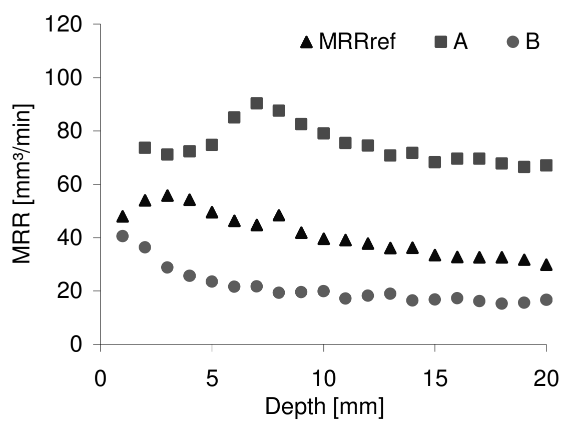

Figure 5: Influence of the machining depth on the MRR (A: 20A, 2x2cm², 5A/cm²; B: 20A, 1cm², 20A/cm²).

More important for the modelling of $C_{flushing}$ is to look at the relation between $C_{flushing}$ and the machining depth. In figure 6 $C_{flushing}$ is shown for the same cases as shown in Figure 5. Figure 6 shows that $C_{flushing}$ is dependent on the machining depth. This means that the machining depth needs to be taken into account in the modeling of $C_{flushing}$. Secondly these experiments showed that there exists a relation between the frontal surface area of the electrode and $C_{flushing}$. This relation is shown in Figure 7 for two current densities when comparing 3 frontal areas at a depth of 5mm. Similar to the results of the influence of the machining depth this figure shows that the relation between the frontal area and $C_{flushing}$ is affected by the current density. In case of low current densities $C_{flushing}$ increases with increasing frontal surface area. Most probably the debris density will increase towards the optimal value when the flushing conditions become worse (e.g. for large frontal areas) because initially the debris density was low due to the low current density. On the contrary in case of high current densities the debris density is initially high so that good flushing conditions are needed to obtain the optimal density. Here most probably large frontal areas accumulate too much debris in the sparking gap leading to a higher than optimal debris density.

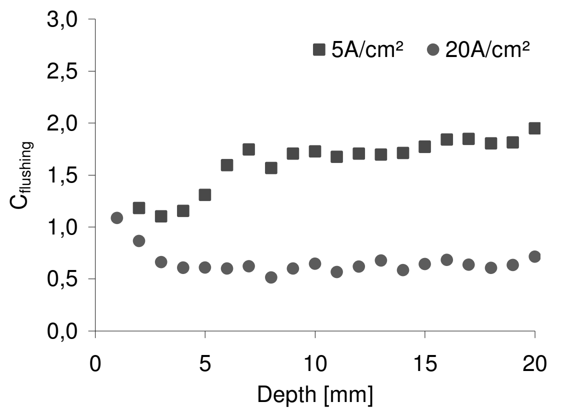

Figure 6: Influence of the machining depth on $C_{flushing}$.

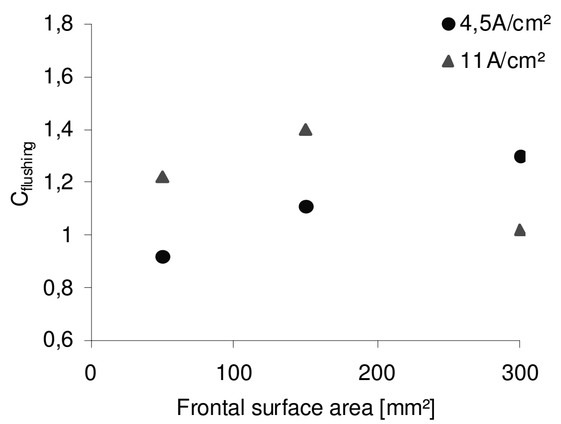

Figure 7: Relation between frontal area and $C_{flushing}$.

Due to the interaction between the current density on the one hand and the machining depth and frontal area on the other hand it was necessary to also include the current density into the modeling of $C_{flushing}$. As a result $C_{flushing}$ looses its initial meaning of a purely flushing related correction factor. Nonetheless $C_{flushing}$ is especially a function of flushing related parameters.

With the determined influencing parameters (machining depth, frontal area and current density) a least squares approximation of second order was applied to all test results in order to develop a model for $C_{flushing}$.

4 TIME ESTIMATION FOR FINISHING OPERATIONS

4.1 Formulation of EDM finishing time

Unlike roughing operations where the focus is on the volume to be machined finishing operations machine the surface of a cavity in order to obtain the required end roughness. Due to the large uncertainty about the volume to be removed during these operations a formulation as in Equation 2 will not be used. Instead of using the MRR the EDM finishing time is used as reference. These reference times ($time_{ref}$) are determined for every generator setting by finishing a pre-machined cylindrical cavity with predefined dimensions by applying a planetary electrode movement (= calibration procedure). On these reference times a correction is applied which takes the deviation from $time_{ref}$ into account.

A finishing operation usually consists of several generator settings, each of them reducing the surface roughness. The total EDM finishing time is then the sum of the machining times of all generator settings applied during a finishing operation (Equation 4).

$$\text{EDM Time}_{\text{finishing}} = \sum_{j=1}^{m} C_{\text{finishing } j} \cdot \text{time}_{\text{ref}_j} \qquad (4)$$

With: j the *j*th finishing generator setting;

m the total number of generator settings;

$C_{finishing,j}$ the correction for generator setting j.

4.2 Modelling of correction on $time_{ref}$

Initial experiments showed that in practice several parameters can explain the deviation from the reference times. The effects of these parameters have been investigated in this research by performing a mixed full factorial design of experiments (DOE). Table 3 lists the selected DOE parameters. Machining length (= machining distance in lateral and frontal direction) and total area (frontal + lateral) were varied over 2 levels while cavity shape and starting roughness were varied over 3 levels. Each experiment consisted of finishing a pre-machined cavity with predefined dimensions (listed in Table 4) with one generator setting (E240: i_e = 6A, t_e = 3.2µs, t_0 = 6.4µs). For each experiment the machining time was logged and $C_{finishing}$ was calculated with the knowledge of $time_{ref}$. Each experiment was executed 3 times and an ANOVA analysis was performed to determine the significant effects. Table 5 lists the results of this analysis for each cavity shape. In this table SS_{effect} refers to the sum of squares between different experiments where the variation could be caused by the change of significant parameters. SS_{effect} is expressed as the percentage of the total sum of squares. R^2 indicates how well a model based on the listed significant parameters matches reality. An R^2 value close to 1 means that the most significant parameters are taken into account to explain the most of the variation.

DOE level	Machining Length [µm]	Total Area [mm²]	Cavity Shape	Starting Roughness [µm]
Low	20	750	Cylinder	1.78
Intermediate	-	-	Rib	1.99
High	60	1400	Square	2.24

Table 3: Selected DOE parameters.

* Each depth corresponds to a level for the total area.

	Cylinder	Rib	Square
Depth [mm]	11.17/22.8*	3.84/8.54*	10.13/21.17*
Dimensions [mm]	Ø16	3.72 x 63.2	13.84 x 13.84

Table 4: Dimensions of pre-machined cavities.

Figure 8 shows the main effects of the selected DOE parameters on $C_{finishing}$. Both machining length and total area strongly affect $C_{finishing}$. A doubling of the machining length results in a doubling of the finishing time. However a doubling of the area results in a finishing time less than the double. The influence of the starting roughness is less pronounced but there is a slight decrease of $C_{finishing}$ noticeable when increasing the starting roughness.

These effects can be explained by considering the volume to be removed during the finishing operation. An increase of the machining length, the total area or a decrease of the starting roughness results in more volume to be removed resulting in a higher machining time.

	SS_{effect} (%)		
Effect	Cylinder	Rib	Square
Machining length	83.41	71.31	72.45
Total area	10.73	20.04	18.51
Mach. Length x Tot. Area	3.47	6.7	7.39
Roughness	1.31	1.09	1.34
R^2	*0.98*	*0.99*	*0.99*

Table 5: Significant effects on $C_{finishing}$ for 3 shapes.

When comparing the three cavity shapes different trends of the investigated parameters are noted. The trends for cavity shapes with corners (rib-like and square cavities) are similar. A large difference exists between the former two cavity shapes and cylindrical cavities. The effects of the machining length and the total area (slopes in Figure 8) are lower for cylindrical cavities. Besides this also the level of $C_{finishing}$ is lower for cylindrical cavities. This means that it takes less time to finish a cylindrical cavity with identical settings, machining length, surface area and starting roughness compared to rib-like and square cavities. The reason for this behaviour can be found in the variation of the energy concentration during one revolution of the planetary electrode movement. In case of cavities with corners the energy is more concentrated in the corners than on the side walls due to the small active area in the corners. Because the electrode rotates at a constant speed less material is removed at the side walls. Hence more revolutions are needed compared to cylindrical cavities where a uniform energy concentration over the entire circumference exists. Because of the strong effect of the shape on the other investigated parameters the modelling of $C_{finishing}$ has been split up into a model for cavities with corners and a model for cavities without corners.

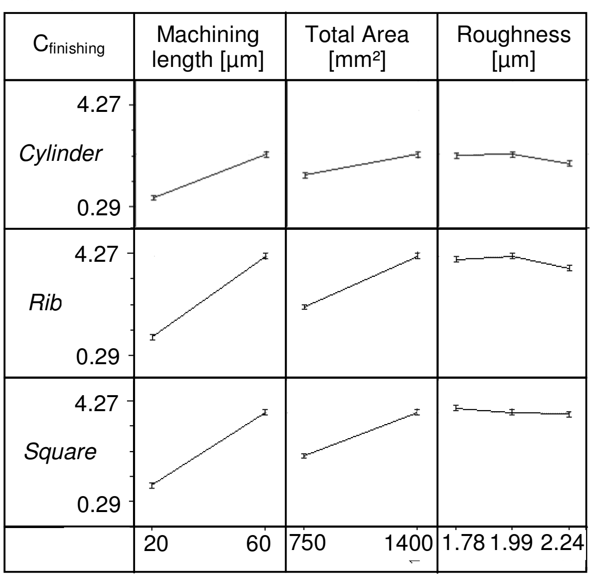

Figure 8: DOE results for 3 cavity shapes.

All these experiments were performed by using only one generator setting. Additional experiments pointed out that the same trends occurred for other generator settings. This means that $C_{finishing}$ is independent of the generator setting.

5 VALIDATION OF DEVELOPED MODELS

5.1 Validation of EDM roughing time model

In order to check the validity of the developed model for estimating the EDM roughing time additional machining experiments were performed. These experiments concerned roughing operations covering the entire range of the developed model (prismatic electrodes, no external flushing, frontal areas smaller than 1000mm², machining depths smaller than 20mm). The real EDM time was compared to the estimated EDM time. Figure 9 shows the error distribution when estimating the EDM roughing time with the developed model. A mean error of 13.8% is noted. In some cases the error even exceeds 100% but this only happens in a small amount of cases. In 91% of all tested cases (579 in total) the error is lower than 25%. Although large errors occur in some cases the developed concept is a large improvement compared to the method which makes use of reference values for the MRR determined by the machine tool builder. Figure 10 shows for the same cases the error distribution when estimating the EDM roughing time by using the former method. Here large errors (mean error: 68.9%) occur in all cases. Note that only positive errors occur i.e. underestimations of the EDM roughing time. So by developing a model for estimating the EDM roughing time the mean estimation error has been reduced with 50%.

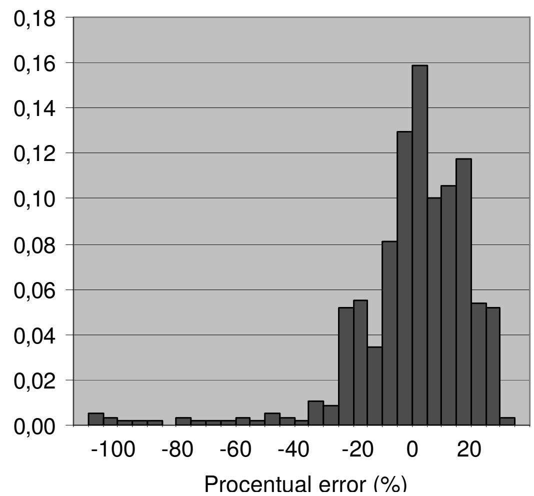

Figure 9: Histogram of errors for EDM roughing time estimation by using the developed model.

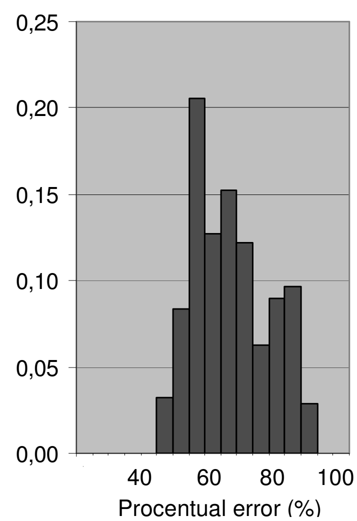

Figure10: Histogram of errors for EDM roughing time estimation by using reference values from the machine tool builder.

	Roughing operations					Finishing operations				
	Real	Estimated time [min]	Error (%)	Machine reference [min]	Error (%)	Real	Estimated time [min]	Error (%)	Machine reference [min]	Error (%)
Case 1	44	43.6	0.9	47	-6.8	111	81.2	26.8	61.4	44.7
Case 2	4	3.8	5	2.6	35.2	6.3	10.3	-62.7	2.3	64.3
Case 3	2.3	4.6	-105.7	0.6	72.2	81.6	39.3	51.8	8.4	89.7
Case 4	9.2	11.3	-22.8	6	35	7.5	11.2	-49.3	1.37	81.7
Case 5	47.2	33	30	26.9	43	50	31.1	37.8	5.9	88.2

Table 7: Results of validation for complex shapes.

5.2 Validation of EDM finishing time models

Similar to the validation of the EDM roughing time model additional experiments were performed to check the validity of the EDM finishing time models. In these experiments only simple prismatic cavity shapes were considered. The results of this validation are shown in Table 6. The developed models give very accurate results (mean error lower than 10% and maximal error lower than 25%) for the considered cases. A comparison with the method of using the reference values from the machine tool builder showed that with the development of the finishing models the estimation error has been reduced with more than 65%.

	Cylindrical cavities		Cavities with corners	
	Mean error	Max. error	Mean error	Max. error
Finishing model	9.61	23.3	6.1	16.6
Machine reference	74.3	81.1	83.9	87.5

Table 6: Validation results for the developed EDM finishing time models and comparison with the time estimation method based on machine reference values.

5.3 Validation for complex machining cases

The validity of the developed models was also checked for the machining of 5 complex shaped cavities. The results are shown in Table 7. As can be expected larger errors occur for these cases, especially for the finishing time. This can be explained by the fact that external flushing was used in these cases which results in a less predictable situation. Besides this, only the main influencing parameters have been taken into account in the developed models. In order to obtain more accurate EDM time estimations also other parameters need to be taken into account (e.g. curvature of bottom surface of the cavity). When compared to the method of EDM time estimation based on the reference values from the machine tool builders Table 7 shows that more accurate results can be obtained with the developed models.

6 CONCLUSIONS

This paper described the development of time estimation models for sinking EDM operations. A new concept based on reference values for either material removal rate or EDM time has been proposed. On these reference values a correction needs to be applied to compensate for deviations from the reference that occur in practice. This study focused on the development of analytical models for this correction. Due to different influencing parameters it was necessary to split up the time estimation problem into the development of a model for roughing operations and a model for finishing operations. For both type of models the effects of the main influencing parameters were identified and included into the models.

A validation of the models showed that accurate results can be obtained for simple prismatic electrode geometries. Compared to existing EDM time estimation methods the developed models are able to reduce the estimation error with 50%. For more complex electrode geometries the developed models give less accurate results. Further research is needed to enlarge the application range of the models e.g. by quantifying the influence of other parameters. This requires a large set of experiments. To avoid this future research can shift to the use of self-learning systems (e.g. neural networks) which can be implemented on the EDM machine.

Within the frame of this research a software tool has been developed for automated EDM time calculations. Based on a STL-representation of the electrode and the appropriate reference values the software automatically calculates the EDM time.

7 ACKNOWLEDGEMENTS

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